

# **Ultralightweight Fresnel Lens Solar Concentrators for Space Power**

**NASA Marshall Contract No. NAS8-99133**

[A NASA Research Announcement (NRA) 8-23 Project]

**M. J. O'Neill and A. J. McDanal**

**ENTECH, Inc.  
1077 Chisolm Trail  
Keller, TX 76248  
Tel: 817-379-0100  
Fax: 817-379-0300  
E-Mail: [mjoneill@entechsolar.com](mailto:mjoneill@entechsolar.com)  
Web Site: [www.entechsolar.com](http://www.entechsolar.com)**

**Draft Final Report  
For Work Performed Under Modification No. 1**

***Lens/Receiver Lengthwise Articulation  
to Eliminate Beta Angle Sun-Tracking***

**For the Period from April 1, 2000 through July 31, 2000**

**August 2000**



## Introduction

The first phase of this project was completed in March 2000, and included the successful technology demonstration of a new ultralightweight photovoltaic concentrator array at the fully functional panel level. The new array is called the *Stretched Lens Aurora (SLA)* array, and uses deployable, flexible, thin-film silicone rubber Fresnel lenses to focus sunlight onto high-efficiency multijunction solar cells, which are mounted to a composite radiator surface for waste heat dissipation. A prototype panel was delivered to NASA Marshall in March 2000, and comprised four side-by-side lenses focussing sunlight onto four side-by-side photovoltaic receivers, as shown in Figures 1 and 2. This prototype panel was tested by NASA Glenn prior to delivery to NASA Marshall. The best of the four lens/receiver modules achieved **27.4%** efficiency at room temperature in the NASA Glenn solar simulator tests. This performance equates to **375 W/sq.m.** areal power and **378 W/kg** specific power at the fully functional panel level. We believe this to be the first space solar array of any kind to simultaneously meet the two long-standing NASA goals of 300 W/sq.m. and 300 W/kg at the functional panel level. Key results for the first phase of the program have been documented by ENTECH in a Draft Final Technical Report, which is presently being reviewed by NASA, and which should be published in the near future.

During March 2000, NASA and ENTECH negotiated a contract modification for a second phase of the project. Under this new phase, ENTECH has performed an additional task related to a novel means of eliminating the need for beta angle sun-tracking for an SLA on a GEO satellite without a major sacrifice in concentration ratio, optical efficiency, or electrical power output. This new approach involves a seasonal lens/receiver lengthwise articulation in place of full array beta angle sun-tracking. Specifically, ENTECH has performed the following new subtasks under the second phase of the project:

- **Develop concepts for the lens/receiver articulation beta tracking approach**
- **Generate a design for the lens/receiver articulation beta tracking approach**
- **Fabricate a proof-of-concept model for the lens/receiver articulation beta tracking approach**
- **Prepare a presentation and participate in Technology Interchange Meeting 3**
- **Prepare a final report documenting key results for this phase of the project.**

The second phase of the project had a performance schedule of four months, with an end date of July 31, 2000.

## Key Results

This phase of the project began on April 1, 2000. To assist in the mechanical design for the lens/receiver articulation beta tracking approach, ray trace analyses were performed and concepts for lens/receiver articulation beta tracking were generated. Figure 3 shows the ray trace results in an end view, and Figure 4 shows the same ray trace results in a side view. Figure 4 also shows a conceptual design approach for a simple articulation of the photovoltaic receiver plane (relative to the lens) to accommodate beta angles of zero, 12 degrees, and 24 degrees. Note that articulation about a point (roughly midway between the lens and receiver) will place the solar cell receiver in the region of best focus for all beta angles in the required annual range (zero to  $\pm 23.5$  degrees) for an SLA on a GEO satellite.

Figure 5 shows the conceptual design of a pivoting lens frame which will implement the seasonal four-bar-linkage articulation of the receiver plane relative to the stretched lens. The four pivot points on each side of the frame will allow the radiator/receiver plane to articulate lengthwise in either direction to accommodate the annual declination angle variation from -23.5 degrees at winter solstice, to zero degrees at spring equinox, to +23.5 degrees at summer solstice, and back again over the following six months. In addition, this frame will be configured to enable the entire assembly (including the stretched silicone lens) to be folded flat for compact launch stowage.

Figures 6 through 8 show a proof-of-concept model, built in to demonstrate the lens/receiver articulation approach. Figure 6 shows the model focussing sunlight with a solar beta angle near zero, with the lens is a full upright position. Figure 7 shows the model focussing sunlight with a solar beta angle of 24 degrees, with the lens articulated relative to the receiver to accommodate this high beta angle. Note that the image is well defined on the black receiver for both beta angles, which represent the minimum and maximum solar beta angles for the year. Figure 8 shows the model in its flattened stow condition.

Figure 9 shows the measured optical performance of a proof-of-concept model tested outdoors at ENTECH, using the short-circuit current output of a 1-cm-wide triple-junction solar cell to determine the focussing performance of the 8.5-cm-wide lens. Measurements were made at three solar beta angles, 0, 12, and 24 degrees, with the lens/receiver articulation at the appropriate position for each beta angle. Two data sets are shown in Figure 9 to demonstrate typical repeatability and data spread due to measurement errors. The short-circuit current measurements were normalized to the same available direct normal solar irradiance (including both the cosine effect and slight variations in pyrliometer-measured irradiance during the tests). Note that all six data points normalize to the small range of 98.6% to 100.0%. Thus, the lens/receiver lengthwise articulation maintains the optical efficiency of the lens at essentially a constant value for all beta angles experienced by an SLA on a GEO satellite over the course of a full year.

A proof-of-concept model, similar to the one in Figures 6 through 8, was delivered to NASA Marshall during the SSP SERT TIM3 meeting in Huntsville June 19-23, 2000.

Both A.J. McDanal and Mark O'Neill of ENTECH participated in TIM3, which included a full presentation of ENTECH program results to date. ENTECH's TIM3 presentation has also been posted on the SSP SERT wing of the NASA VRC web site. ENTECH personnel also participated in their assigned working group and integrated product team during TIM3.

### **Conclusions and Recommendations**

Key conclusions drawn from the work under Modification No. 1 include the following:

- The new lens/receiver articulation approach has been shown to work very well in eliminating the need for beta angle sun-tracking for the SLA on a GEO satellite.
- The optical performance of the articulated SLA on a GEO satellite will be essentially constant over the full year. (Of course, the beta angle cosine effect will still apply, just as it does to a single-axis tracking planar array, and eclipse periods will still take place near the equinoxes for all array types.)
- The beta angle articulation approach is relatively simple in mechanical details, and should be relatively easy to implement on large SLA arrays on GEO satellites. A four-bar-linkage system could be driven with a linear actuator, which would only need to be adjusted every few days to maintain necessary precision, since the maximum rate of beta angle change is about 0.4 degrees per day near equinox.

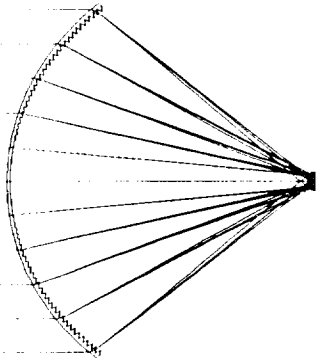
Key recommendations drawn from the work under Modification No. 1 include the following:

- The new beta angle articulation approach should be included in future SLA prototype panels to enable full AM0 performance testing at beta angles of 0, 12, and 24 degrees.
- Simple means of driving the four-bar-linkage seasonal beta articulation should be designed, developed, and tested.
- Trade studies should be performed to quantify the advantages of the beta angle articulation approach compared to full two-axis sun tracking in terms of system-level mass, cost, and attitude control fuel savings.

### **Figures**

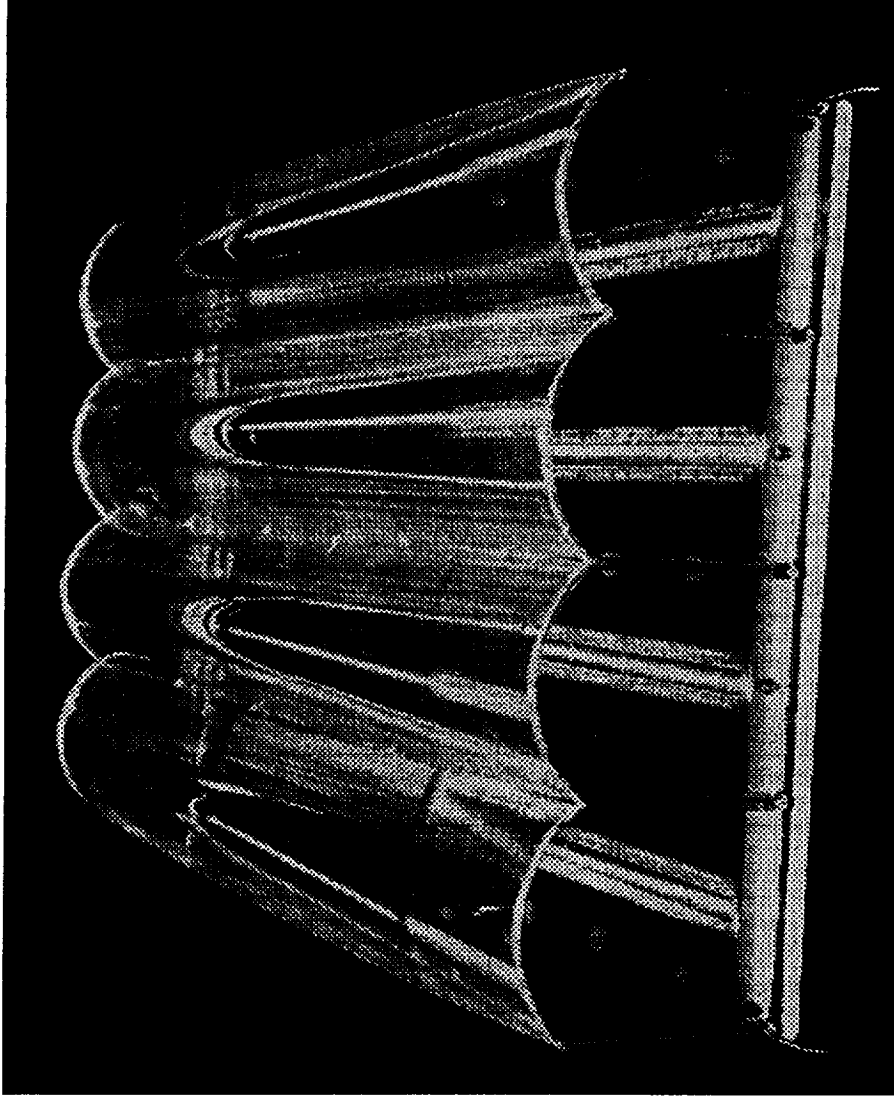
The nine figures referenced above are provided on the attached nine pages.

## SLA Prototype Under Test at ENTECH

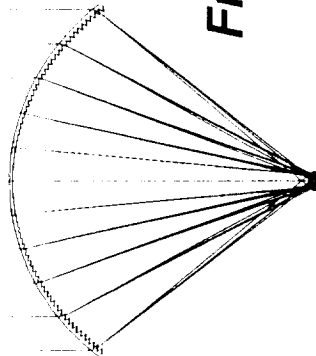


◆ In March 2000, NASA GRC Tested the SLA Prototype Panel at Unprecedented Performance Levels:

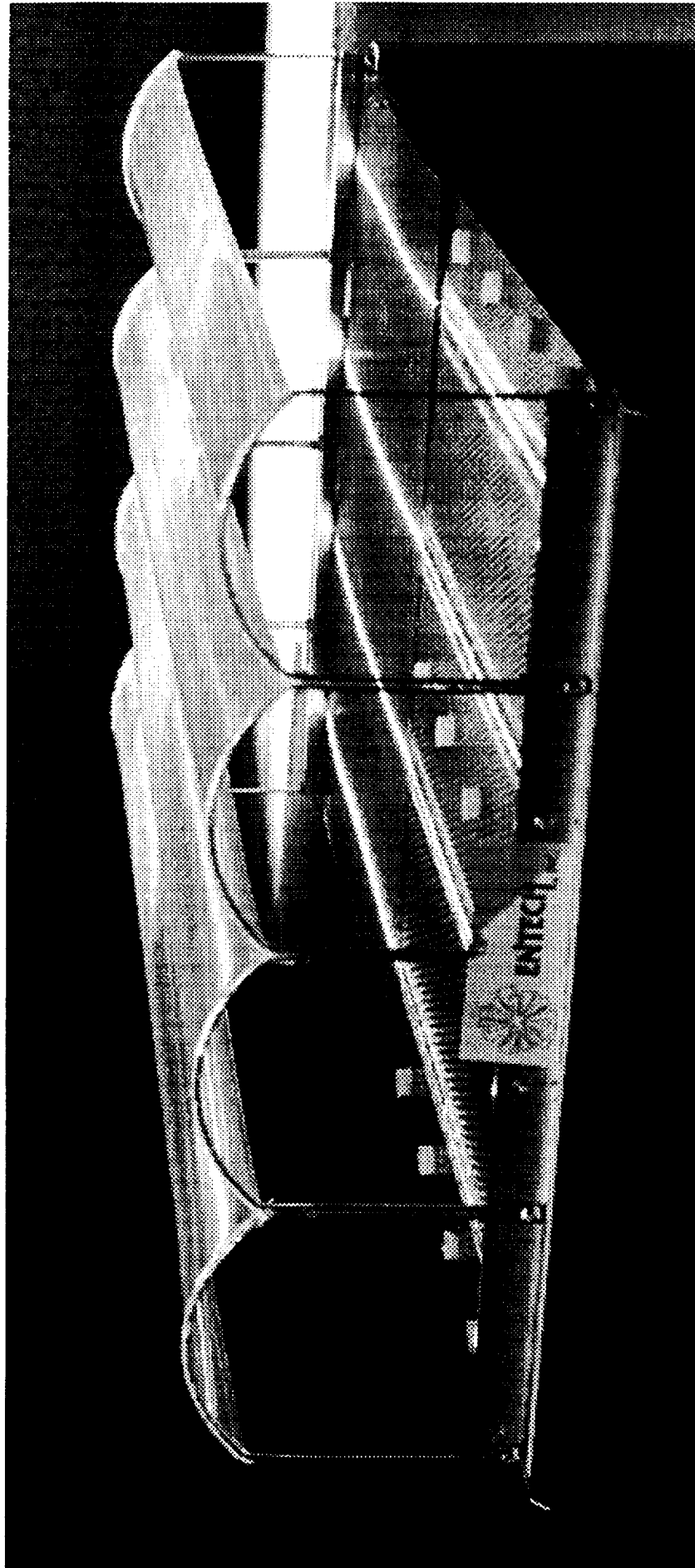
- 27.4% Efficiency
- 375 W/sq.m.
- 378 W/kg at Panel Level
- All Measured at 20C Under AM0 Irradiance

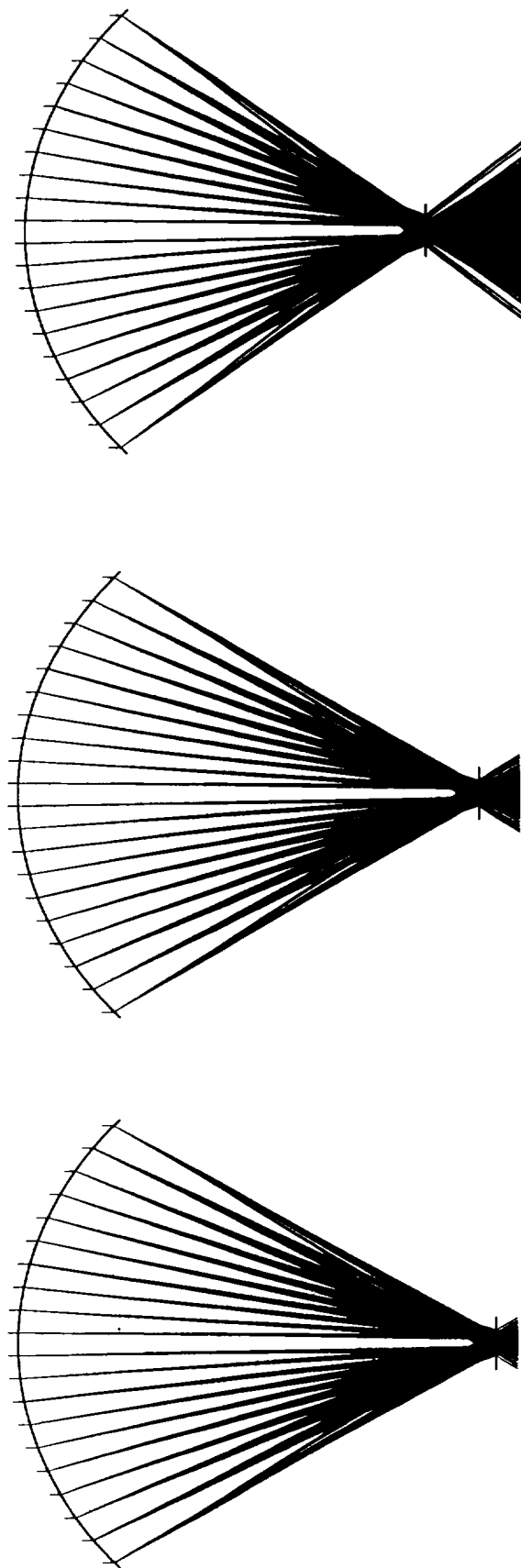
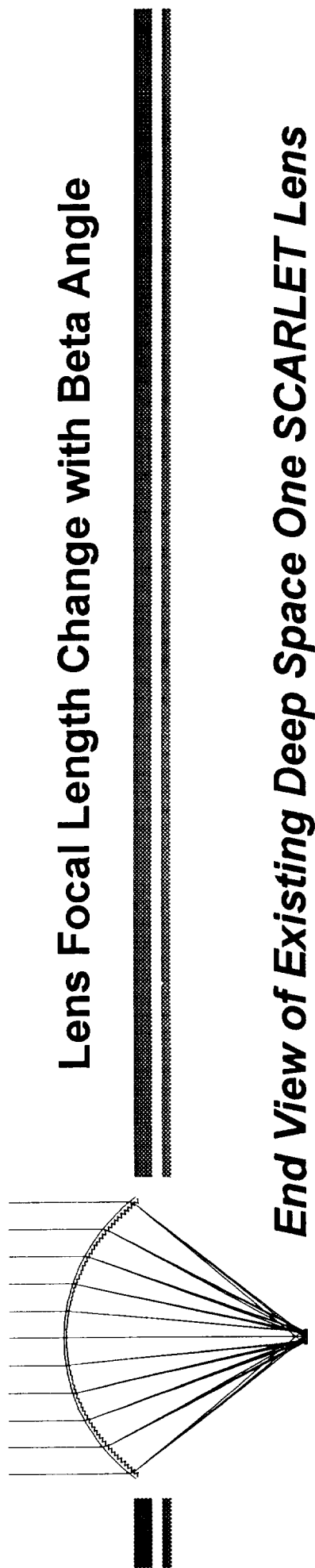


## End View of SLA Prototype

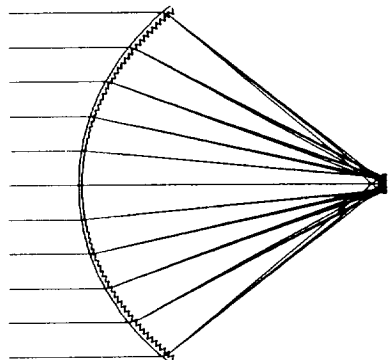


*Front Panel Active, Back Panel Shielded with Overlay Sheet*



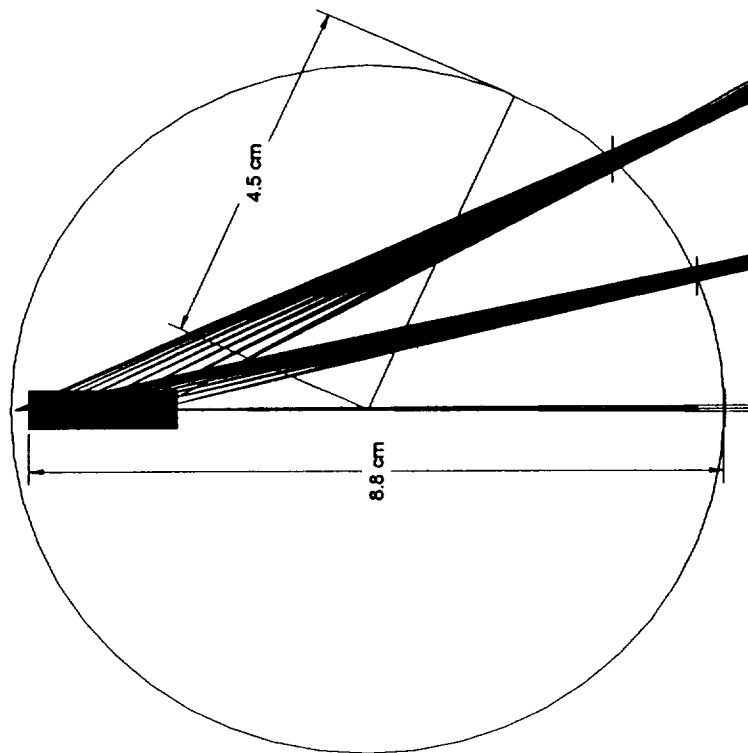


**Beta = 0 degrees**      **Beta = 12 degrees**      **Beta = 24 degrees**



## Lens/Receiver Beta Articulation to Maintain Focus

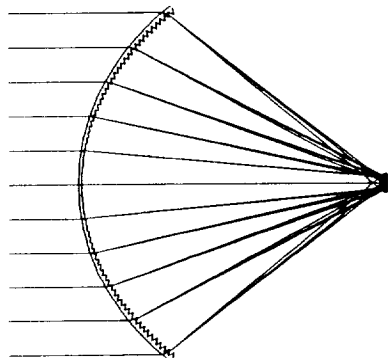
### Side View of Existing Deep Space One SCARLET Lens



- ◆ To Accommodate Solar Declination Angle Variations Throughout the Year:
  - Beta Incidence Angles Will Vary from Zero at Equinoxes to  $\pm 23.5$  degrees at Solstices
  - For the Existing Deep Space One SCARLET Lens, Ray Traces, at Zero, 12 degrees, and 24 degrees of Beta Angle, Show that a Simple Four-Bar-Linkage Articulation of the Receiver Plane, Relative to the Lens, Will Maintain An Excellent Focus

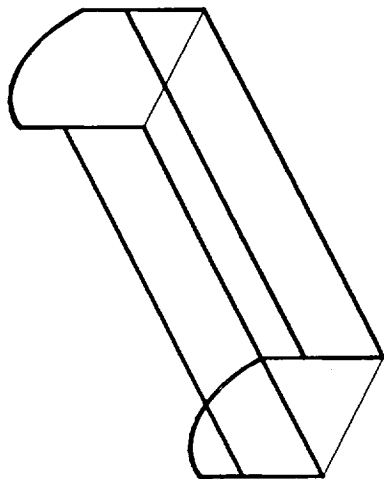






## Schematic of Beta Articulation Frame

*Isometric Sketch*

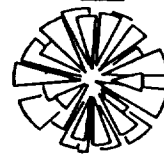
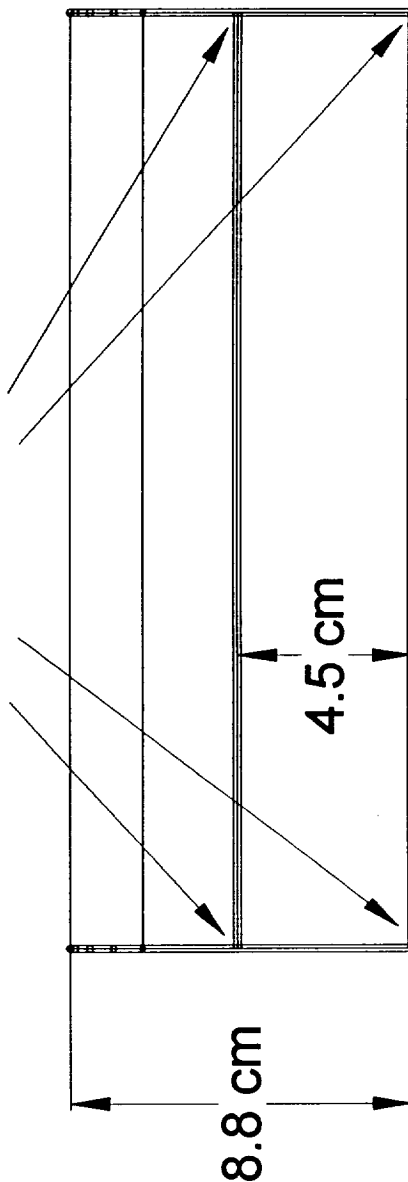


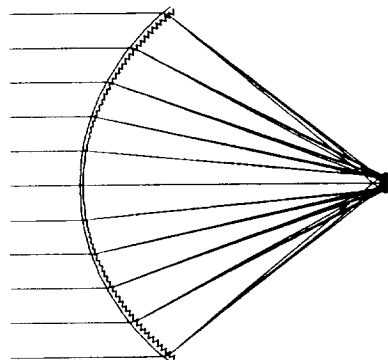
◆ **Frame Folds Flat for Stowage**

**◆ Receiver Plane Articulates Seasonally Relative to Lens**

*Side View*

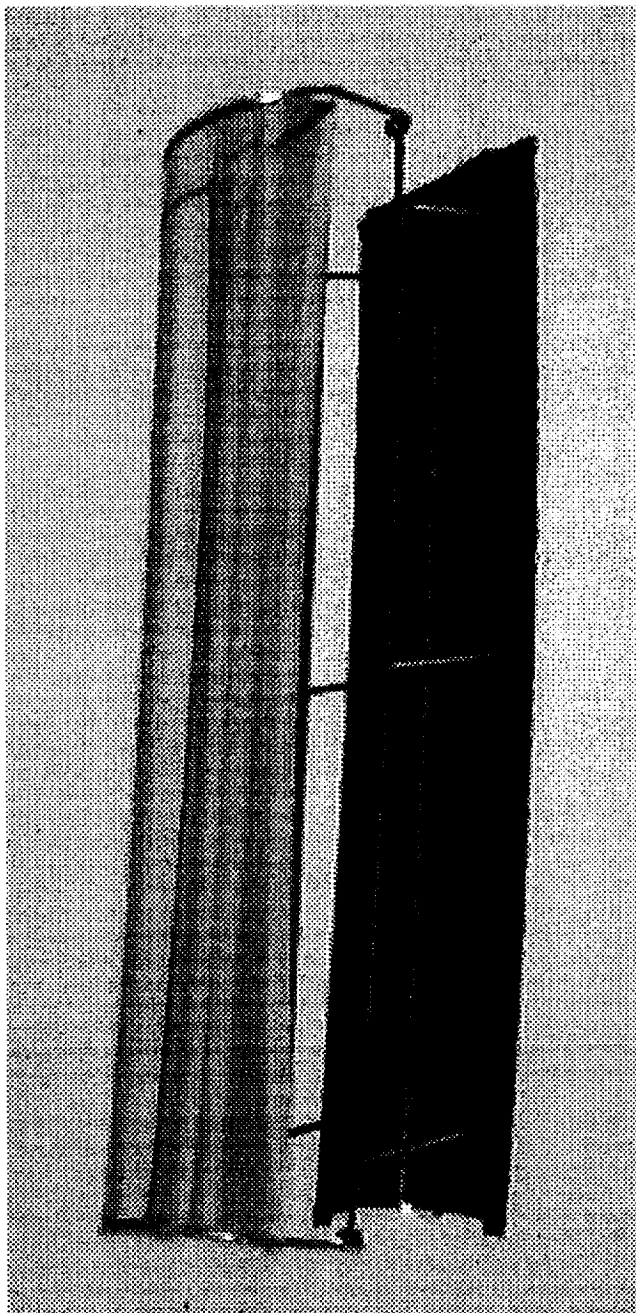
Pivot Points

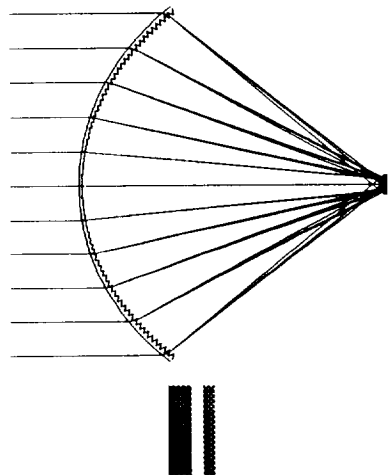




## Prototype Beta Model Focussing Sunlight

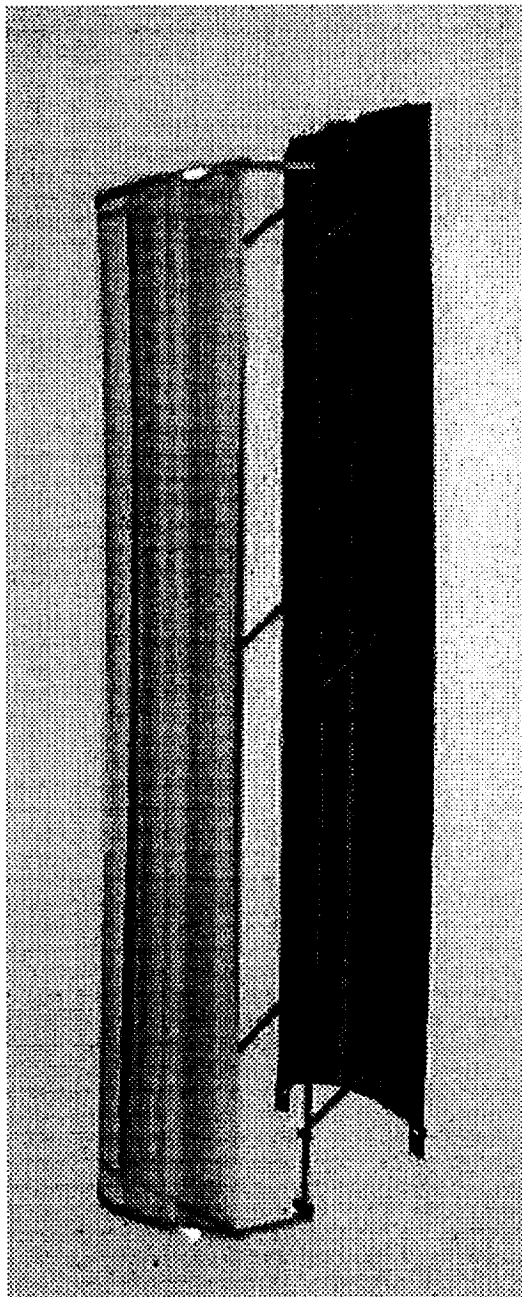
*Solar Beta Angle Near Zero*

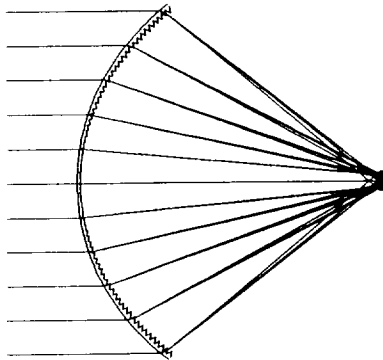




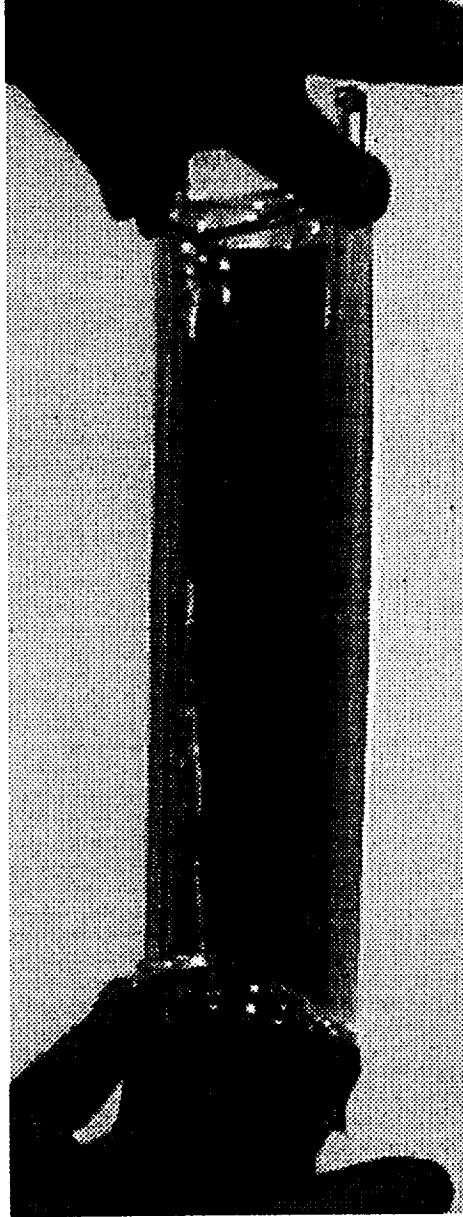
## Prototype Beta Model Focussing Sunlight

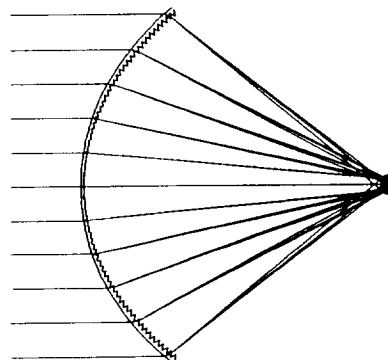
*Solar Beta Angle = 24 degrees*



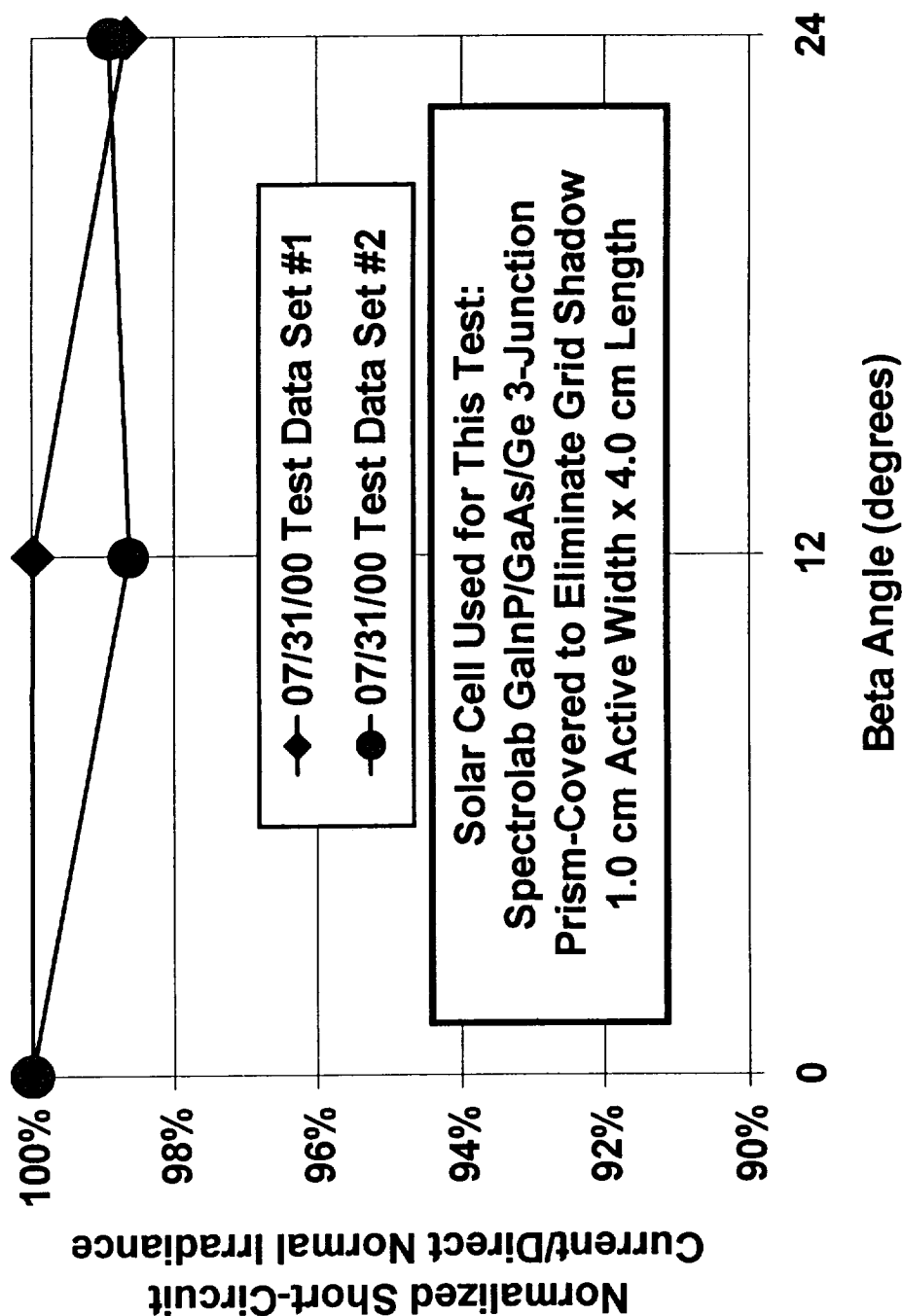


## Prototype Beta Model Flattened for Stow





# Outdoor Test Results for Prototype Beta Model



**Optical Performance Is the Same Over the Full Beta Range Within Experimental Error Margin**

<b>REPORT DOCUMENTATION PAGE</b>			Form Approved OMB No. 0704-0188	
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